THE RUNNELLING METHOD OF HABITAT MODIFICATION: AN ENVIRONMENT-FOCUSED TOOL FOR SALT MARSH MOSQUITO MANAGEMENT

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ABSTRACT. Traditional methods of managing salt marsh mosquitoes focus primarily on maximizing the reduction of mosquito populations, with minimizing environmental impact as a secondary consideration. An environment-oriented approach to salt marsh management for mosquito control, runnelling, is described and compared with other forms of habitat modification such as ditching and Open Marsh Water Management (OMWM). Runnelling alters the salt marsh as little as possible while causing significant reductions in mosquito numbers. The effect of runnelling on the environment was monitored via the following variables: water table level, substrate characteristics (moisture, salinity and pH), vegetation (height and density of each *Sporobolus virginicus*) and the numbers of mosquito larvae. Runnelling had a statistically significant effect on only two of the seven variables. These were the height of *Sporobolus*, which increased near runnels, and the number of mosquito larvae, which decreased. The main difference between ditching, OMWM and runnelling lies in the magnitude of the habitat modification. Ditching involves the greatest alteration to the marsh, and runnelling the least. Consequently, runnelling has a smaller effect on the estuarine environment as a whole than does either ditching or OMWM.

INTRODUCTION

Salt marshes are highly productive areas which are important to the functioning of adjacent wetland systems. They maintain an ecological "bank" which supplies nutrients to estuarine systems, and act as physical buffers between marine and terrestrial environments. Their role has been recognized by many (Kalber 1959, Odum 1961, Taylor 1974, Shisler 1979, Turner 1982, Daiber 1986a). Because of interactions between marsh and estuarine and, hence, marine environment, any disturbance of the former is likely to have repercussions on the latter (Turner 1981). This needs to be taken into account when planning and implementing marsh management.

It is the sheer abundance and productivity of mosquitoes that has often drawn people's attention to salt marshes. Attempts have been made to reduce the problem by direct physical attack on the environment, rendering it unsuitable for mosquito breeding, and/or by chemical/biological assault on the mosquito itself. Ditching and impounding exemplify the former; insecticide use is an example of the latter. These were all aimed primarily at exterminating the pest, with little regard to, or ignorance of, the environmental consequences. Deleterious environmental effects and subsequent public opposition led to the development of less destructive methods such as Open Marsh Water Management (OMWM). This approach aims to reduce mosquito populations to acceptable levels while actively maintaining marsh processes.

In seeking a method which would satisfy both mosquito control requirements and the need to maintain environmental integrity, we commenced studies, in 1981, of a salt marsh ecosystem at Coomera Island 70 km south of Brisbane, Queensland (270° 52′S 153° 23′E). Our aim was to control numbers of *Aedes vigilax* (Skuse) mosquitoes known to be a major pest and vector of Ross River virus (Kay et al. 1981). Given the importance of the salt marsh's ecological function, its conservation was central to the rationale of planned environmental modifications using a system of wide shallow spoon shaped channels called "runnels." Runnels follow natural flow routes of water, connecting salt marsh pools to adjacent mangrove and estuarine systems, thereby enhancing the movement of water over the marsh.

In this paper, we introduce runnelling as an environment-focused method to manage salt marsh mosquito populations, report on its impacts on the salt marsh and distinguish it from ditching and OMWM as described by Meredith et al. (1985).

METHODS

Preconstruction: Using color infrared aerial photographs and field data, we identified larval habitats (Dale et al. 1986) and natural water bodies or channels. We mapped pools, natural watercourses (channels), incipient and potential watercourses. A runnel system was planned to connect the pools and channels to an estuary, taking into account the local relief and patterns of flooding over the marsh. Pools which were relatively isolated were designated for filling with spoil from the runnels.

Runnel depth was determined to avoid erosion and to maximize larval mortality. Substrate

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characteristics were measured (Law, unpublished data), and meteorological data (Commonwealth Bureau of Meteorology) were obtained for this purpose. To avoid erosion, runnels were designed so as not to breach the subsurface sandy layer. To maximize larval mortality, pool depths were designed so that, if they had not drained, they would dry up after a flooding period before larvae would be likely to complete their development. This depth was calculated from the mean daily evaporation and percolation rates in relation to the developmental times of *Ae. vigilax* during summer.

Construction: An area of 0.5 hectares was runnelled, and this and an untreated area of 2.0 hectares were monitored for larvae. Runnels were constructed by hand along the planned layout and checked for appropriate gradients and direction of slope. To minimize erosion, gradients were slight (often <1:1000), and followed natural drainage lines where possible. Each channel was at least three times wider than deep, with smooth, gently concave sides and bottom. A depth of less than 20 cm was preferred, to remain above the sandy layer, to minimize effects on the water table and because breeding sites less than about 18 cm deep would generally dry up naturally before adult eclosion, notwithstanding rainfall. Spoil from runnels was placed in pools designated for filling rather than leaving it as mounds or levees. This eliminated mosquito breeding sites, avoided raising marsh levels and, hence, changing substrate moisture and salinity, and this, in turn, prevented the invasion and colonization of nonsalt-marsh plants (see Kuenzler and Marshall 1973).

Evaluation: To evaluate the effects of the modification, we commenced monitoring the runnelled area 3 months prior to construction which took place in November 1985 and plan to continue monitoring until 1995. During the first year we monitored the marsh on a monthly basis, and thereafter on a quarterly one. Observations dates were based on lunar months so that records were standardized with respect to stage of the tidal cycle. Here we report results from September 1985 to November 1986 for nontarget aspects of the environment and from December 1985 to November 1988 for mosquito numbers.

Larval distribution: We monitored larval distributions by recording numbers of larvae per 240 ml dip in the 0.5 ha runnelled area and 2.0 ha of unrunnelled marsh. Three dips per pool or section of runnel were taken. We have not tested for statistical differences between the numbers of larvae in treated and untreated areas because our primary concern is the effectiveness of the method in reducing numbers to below the level at which larvicidal treatment is required. We counted the number of pools and other sample sites with/without larvae both in the runnelled area and in the untreated marsh. The relationship was tested by Chi-square analysis. We also recorded the presence of fish in runnels and pools. Each time we saw fish in a water body it was recorded as an occasion.

Layout of transects and sampling points: In a highly heterogeneous environment such as the salt marsh it is extremely difficult to find comparable areas to use as controls in experiments. For the Coomera Island study, we avoided this problem by means of a multivariate analysis of processes occurring in the whole study area and comparing the treatment and pseudo-control samples for differences in their processes of change (Dale and Hulsman 1988).

To evaluate impacts on nontarget aspects of the environment we monitored the water table level, substrate characteristics [moisture, salinity and reaction ("pH")] and vegetation (size and density of *Sporobolus*). There were seven transects, one was approximately 66 m long containing 36 sample points and ran from the inlet towards the center of the marsh. The remaining six transects were short (4 m) containing four sample points. Four of these short transects were adjacent to runnels, and two were adjacent to pools. In addition, two short transects adjacent to a pool were a subset of the long transect. Transects adjacent to pools were regarded as pseudocontrols. Samples were taken along the transects at right angles to runnels and natural water bodies, sampling near the edge and at distances of 1, 2 and 4 m from it to detect any variation in water table, etc., owing to distance from the pool or the runnel.

Water table: The height of the water table was measured by the distance the water level was from the top of a stand pipe. The top of each pipe was the same height above the local datum.

Substrate characteristics: A 70-gram sample of surface substrate was taken from each of the 60 sampling points at each sampling time and transported in sealed plastic bags to the laboratory. Substrate moisture was determined from 50 grams of substrate which was weighed and placed in an aluminum tray. The sample was dried in an oven, set at 105°C, for at least 2 days until the sample's weight stabilized. The moisture content is given by the difference in the wet and dry sample.

The substrate salinity and reaction were determined by creating a mixture of one part soil to 5 parts water for each of the 60 samples. We added 100 cm^3 of deionized water to 20 grams of substrate then agitated the mixture in a mechanical shaker for one hour. After the suspended particles settled on the bottom, usually an hour after agitation ceased, we measured the salinity with a YSI salinity meter and the pH of the solution with a TPS pH meter. These measurements were then corrected to give the substrate moisture salinity and reaction.

Vegetation: Adjacent to each of the 60 stand pipes a 10 × 10 cm plot was marked with twine. The number of tillers of *Sporobolus virginicus* in each of these plots was counted. The height of 10 tillers in each plot was measured.

RESULTS

Distribution of larvae: During the first 3 months after the runnels were constructed (i.e., summer December 1985 to February 1986) there were large numbers of larvae on the marsh as a whole (Fig. 1). In fact, the breeding was so heavy that both the runnelled and unrunnelled areas required chemical treatment. But thereafter the runnelled area has had significantly fewer mosquito larvae than the unrunnelled area (Fig. 1). The number of mosquito larvae in the runnelled area has been reduced to the extent that larviciding has not been required since February 1986 up to and including November 1988 whereas larviciding has been required in the unrunnelled area on 5 occasions (see Fig. 1). The criterion used to determine whether or not to treat an area with larvicide was the occurrence of 5 or more larvae/dip in at least 20% of the dips.

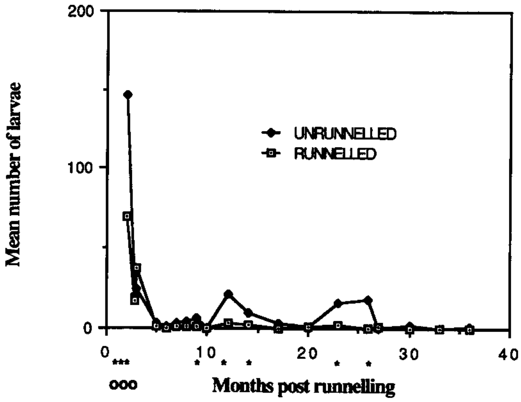

Fig. 1. Mean number of larvae per dip in the runnelled and the unrunnelled areas from 2 to 36 months after the runnels were constructed, i.e., from January 1986 to November 1988. The symbol O indicates treatment with larvicide was required in runnelled area and * in the unrunnelled area.

Table 1 shows the frequency of each instar and pupae in the runnelled and unrunnelled areas on 5 of the occasions that the unrunnelled area required treatment with larvicide. There was a distinct lack of first instar larvae in the runnelled area when they were abundant in the unrunnelled area.

There were large differences between treated and untreated areas in the number of pools and channels containing larvae. In the runnelled area 27% of sites contained larvae (1–2 per dip), whereas larvae were abundant in all sites in the untreated area, with a dip containing up to 670 larvae.

The increased access of fish to the marsh is reflected in the far greater frequency with which fish were observed in the runnelled area. For example, we found fish in the runnelled area on 126 occasions but only on 9 occasions during the same period in the unrunnelled area. Moreover, where fish occurred there were invariably fewer larvae than where fish were absent. For example, water bodies with fish contained no larvae on 123 of the 126 occasions in the runnelled area and on 6 of the 9 occasions in the unrunnelled area.

Between January 1986 and October 1987, for example, there were consistent differences in the presence/absence of larvae in the two areas. In the runnelled area, only 22% of sites contained larvae compared to 62% of sites for the untreated marsh. Table 2 shows the frequency of larval presence/absence in treated and untreated sites for the abovementioned period.

Environmental impacts: The multivariate analyses indicted that runnelled sites were not significantly different from other sites over the 15 month period (3 months pre- and 12 months post-runnelling) ($P > 0.05$).

There was no marked effect on any of the substrate or water table variables. Mean values for substrate reaction, substrate moisture and

Table 1. Number of each immature stage of mosquitoes in the runnelled and unrunnelled areas on 5 occasions, when the unrunnelled area required treatment with larvicide. Note that the runnelled area required treatment in February 1986 but not on the other occasions.

	Runnelled					Unrunnelled				
Date	1*	2	3	4	P	1	2	3	4	P
Feb. 1986		5	216	156		8	125	486	201	
Aug. 1986			3	2			15	184	57	
Jan. 1987		3				1,056	269	11		
Oct. 1987				3	4			2	62	32
Jan. 1988						19	103	137	66	19

* Instars 1–4 and pupae.

its salinity show that, although there were differences between sites adjacent to pools and those near runnels, those differences were maintained after runnelling for at least a year (Fig. 2a–c). A slight lowering of the water table close to runnelled sites was observed. Figure 2d shows that prior to treatment water table levels close to sites scheduled for runnelling were slightly higher than those close to pools. This relationship was reversed after treatment, although the differences are small (2.0–8.5 cm) and are not statistically significant.

Table 2. The relationship between runnelling and the presence/absence of larvae at sample points (January 1986–October 1987)

	Runnelled area	Untreated marsh	Total
Sites with larvae	56	178	234
Sites without larvae	200	108	308
Total	256	286	542

$\chi^2 = 89.67$; $df = 1$; $P < 0.001$.

Runnelling apparently did have a marked effect on the mean height but not on the mean density of marine couch, *Sporobolus virginicus* (Fig. 2e–f). The largest difference was in the increased height of *Sporobolus* in sites adjacent to runnels, compared to the decreases in size of *Sporobolus* in sites near pools (Fig. 2e). This effect was most pronounced in sites at a distance of 4 m from the runnel (not shown in Fig. 2). Although the density of *Sporobolus* decreased in

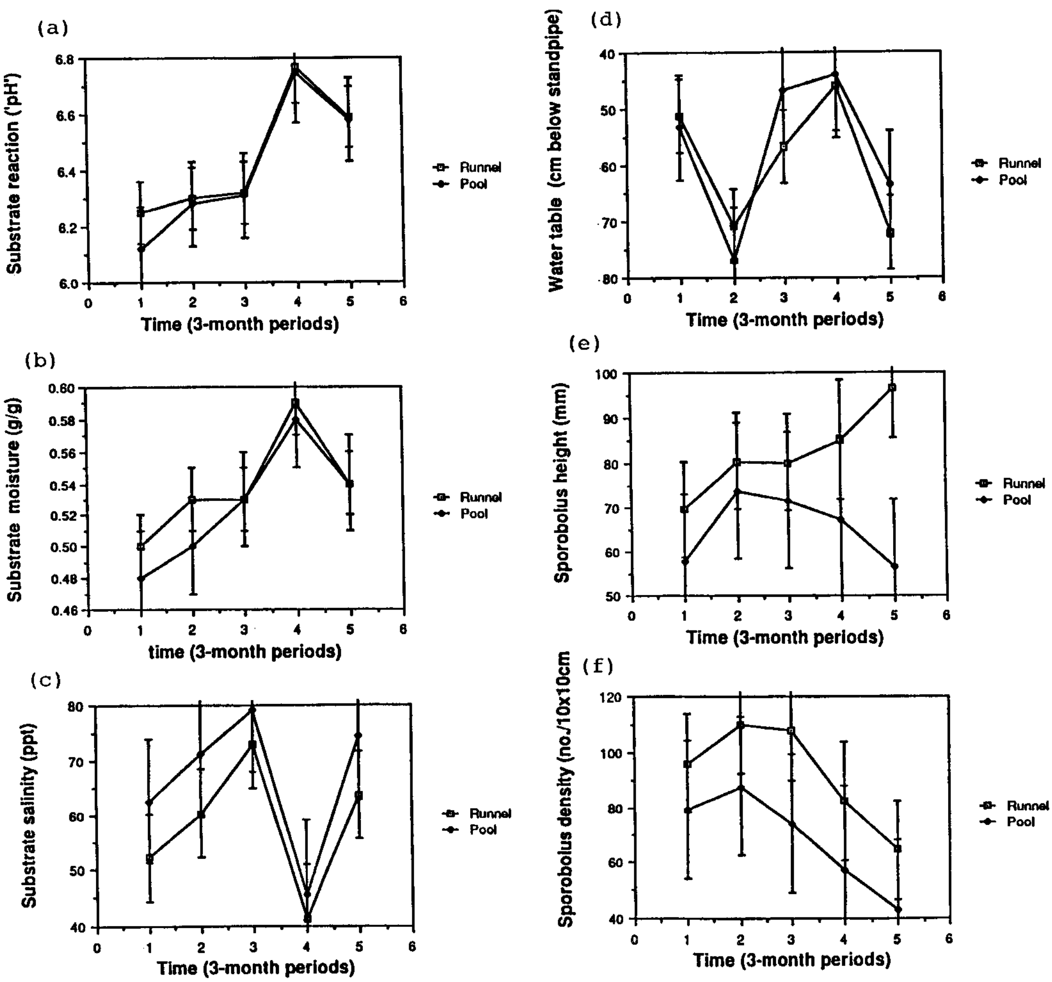

Fig. 2. Mean values (3-month periods) and 95% confidence limits for variables measured at 0, 1, 2 and 4-m distances from pools and runnels, between September 1985 (pre-treatment) and November 1986. Variables shown are: (a) Substrate reaction ('pH); (b) substrate moisture; (c) substrate salinity; (d) water table height; (e) *Sporobolus virginicus* height and (f) *Sporobolus virginicus* density.

both untreated and treated sites, the decrease was not associated with runnelling *per se* (Fig. 2f).

DISCUSSION

Runnelling is an effective means of reducing larval numbers to below the threshold which would activate the spraying of a larvicide. Of the 20 observation periods shown in Fig. 1, there would have been a need to spray on eight occasions in the unrunnelled area as compared to 3 times in the runnelled area. Note, however, that the 3 larvicide treatments in the runnelled area were required during the first 3 months after the runnels were constructed.

Runnelling operates in a manner which is similar to the "open" system parts of OMWM, that is, by facilitating predation on larvae and by physically transporting larvae off the marsh. Increased access to the marsh during high tides may allow predatory fish to visit the pools and feed on larvae (Morton et al. 1987, Morton et al. 1988). As water recedes, fish leave the system for deeper estuarine waters. We have observed that larvae are often flushed into the estuary where they presumably drown or are eaten.

This flushing may only occur if water flow is relatively slow. Our observations indicate that larvae avoid rapidly flowing water. They anchor themselves to vegetation or take refuge in uneven terrain. However, when water flows slowly larvae drift and, at times, swim with the flow. This observation is consistent with the few measurements of flow rates by determining the rate at which dye travelled 5 meters. In the runnelled area, the mean rate of water movement was 5.48 m/min (SD = 2.55 n = 9) and larvae were drifting downstream. Some 100 m to the north of the runnelled area, a channel contained rapidly flowing water (mean = 31.28 m/min, SD = 15.19, n = 10). Although larvae were present in the headwaters of this channel, none was observed moving along the channel.

During the first 3 months after the runnels were constructed, they were relatively ineffective in reducing numbers of mosquito larvae to a level that rendered treatment unnecessary. But thereafter, runnels were effective and larviciding was not required while the unrunnelled area required five treatments (Fig. 1). In stark contrast to our results, Hruby et al. (1985) reported that OMWM methods reduced numbers of mosquito larvae and pupae significantly within a month of the marsh being altered. We are confronted with the problem as to why did the runnels not become immediately effective. One reason is that the runnels could not cope with the large numbers of larvae on the marsh. Since then, larval numbers have generally been lower. There are other possible explanations for delayed effectiveness. If flushing larvae from the marsh was the main mechanism for reducing numbers of larvae, then the runnels should have been effective immediately. One explanation is that the decrease in numbers of larvae may have been caused by increased but delayed predation. If there was a delay in the increase in the number of predators through immigration in response to increased access to food, including mosquito larvae, then this would be reflected in the slow decline in numbers of larvae. Another possibility is that runnelling progressively decreased the suitability of the area for oviposition and thus the decline in numbers of larvae in the runnelling area. Both of these suggested explanations require further investigation to test their feasibility.

A further difference between the runnelled and unrunnelled areas was in the paucity of first instar larvae in the former at times when they were numerous in the unrunnelled area (Table 1). There are several factors which would help to account for this.

One is that oviposition may have been reduced; another is increased predation of first instars. If predatory fish visit the area as a flooding occurs, they are likely to consume recently hatched first instar larvae. Secondly, the presence of large numbers of predators may elicit an escape response in the larvae which may use the runnels to "escape" to the estuaries where they drown or are eaten. In the untreated area, however, fish were fewer and many isolated pools contained none at all. In such places, larvae can and do develop through all larval stages, as is shown in Table 1.

An additional factor is that fish, even small ones, will be more effective at reducing early instar larvae than later ones simply because of the larval size difference. This is exemplified by *Culex sitiens* Wied., another pest species that is occasionally numerous on the marsh. An average first instar larva of *Cx. sitiens* (0.02 mg) is twice as small as a second instar larva (0.04 mg), 19 times smaller than an early third instar (0.39 mg), 54 times smaller than a late third instar (1.08 mg) and 170 times smaller than a fourth instar larva (3.40 mg) (Hulsman and Dale, unpublished data). Therefore, a small larvivorous fish eating 170 first instar larvae would obtain the same biomass as if consuming one fourth instar larva. Hence, fish access to the first instar in the runnelled area may provide more effective control than access to later instars, simply because larger numbers of larvae can be consumed.

Ditching, OMWM and runnelling compared: All 3 methods are effective at reducing the pest problem. The most important physical differences between the three methods are summa-

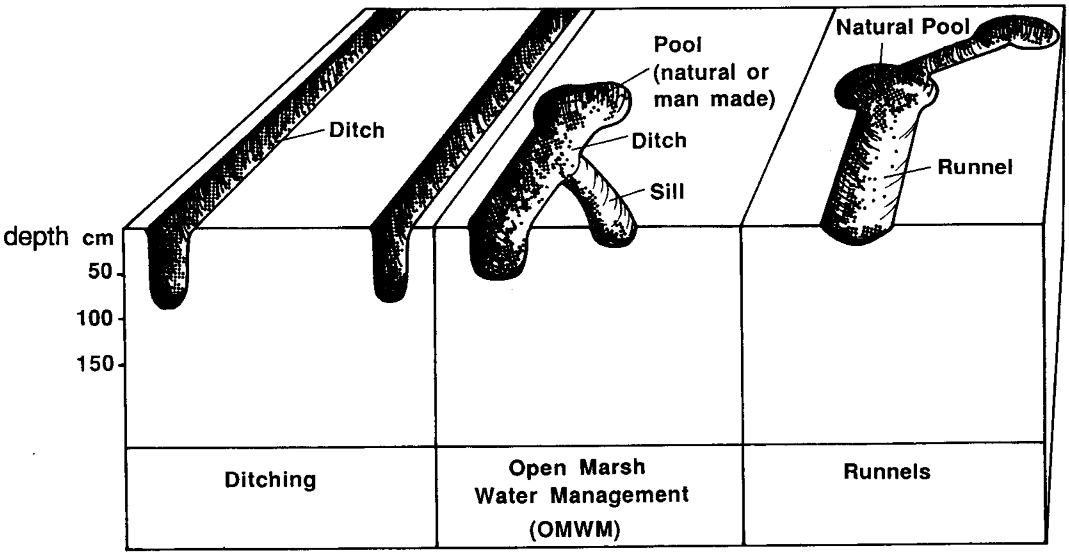

Fig. 3. Ditching, OMWM and runnelling—structures and layout.

Table 3. Comparison of some characteristics of ditching, OMWM and runnelling.

Characteristic	Ditching	OMWM	Runnelling
Hydrology	Drains	Increases circulation and retains reservoirs for fish	Increases flushing
Channel pattern	Regular (often parallel grid)	"Natural looking"	Follows lines of natural flow of water
Channel depth	60–90 cm	Tidal ditch: 75 cm Sill: 10–20 cm	Normally <20 cm
Channel width	Narrow	Narrow	At least 3 × depth
Channel shape	Steep, often vertical sided	Steep-sided	Gently sloping concave sides

rized in Fig. 3 and Table 3. The main difference lies in the amount of alteration involved. Ditching uses deep, steep-sided channels in a superimposed, often regular, pattern. In OMWM both steep-sided deep ditches and shallower sills are constructed to connect pools to tidal creeks. Additional pools are dug as reservoirs for marsh organisms. An objective of OMWM is to make a "natural" looking environment (Meredith et al. 1985). Runnelling involves very shallow channels and uses the preexisting water flow network as a template for the layout. This determines the spacing of runnels and ensures a natural pattern.

Table 4 summarizes and compares the main effects of the 3 methods. In terms of the hydrology, the most important variable in the system, ditching has the greatest effect, dewatering the marsh, and runnelling the least, enhancing flow. Ditching imposes a channel network on the natural system and so, to a lesser extent, does OMWM. Runnels, designed with nature, should have minimal impact on marsh hydrology, as they merely enhance extant processes. Overall, ditching has the greatest effect, radically altering the environment. OMWM has less "catastrophic" effects and tends to increase productivity and wildlife on both the eastern (Shisler 1979, Meredith et al. 1985) and western seaboards (Resh and Balling 1983b).

There are important differences in the operation of runnelling and OMWM. As well as the "open" system, which is similar to runnelling, OMWM also employs a relatively "closed" system wherein deeper reservoir pools and radial ditches are not directly connected to the estuary. These fill on the highest tides and are intended to maintain populations of fish and other organisms on the marsh. The runnel system has no on-marsh reservoirs but makes use of the naturally occurring "open" reservoir of the estuary and deeper inlets to sustain the fish populations.

Table 4. Some effects of ditching, OMWM and runnelling.

Variable/Process	Ditching[1]	OMWM	Runnelling[6]
Variables			
Open water volume	Increased[1]	Increased	Similar
Water table height	Lowered[2,3]	Slightly lowered	No significant effect
Soils	Drains, dries, reduces salinity	Reduced salinity close to ditches[3]	No significant effect on soil moisture or salinity
Vegetation spp	Low marsh spp replaced by high marsh spp[2]	Tends towards marsh spp	No change in species or density. Height is affected.
Animals	Increase in nonmarsh organisms. Decrease in invertebrate fauna[2]	Increased populations of most spp. No biomass change[3] Decreased diversity[4]	Increased numbers of fish using the marsh.[7] Increased crabs.
Heterogeneity (marsh)	Reduced	Increased (?)[3,4]	Little effect, possibly increased
Processes			
Plant productivity	Increased[2]	Increased[2,3]	Little change
Tidal flushing	Decreased when drained	Increased[4]	Increased
Nutrient, organism, material transfer with adjacent systems	Decreased[2]	Slight decrease, (?)[2]	Unknown

(?) Uncertainty or lack of information on effects.
[1] Kuenzler and Marshall (1973).
[2] Daiber (1986b).
[3] Resh and Balling (1983b).
[4] Resh and Balling (1983a).
[5] Lesser et al. (1976).
[6] Dale and Hulsman (1988); Hulsman and Dale (1988).
[7] Morton et al. (1987).

There is a further difference between OMWM and our method. Runnels are designed such that pools which they connect are too shallow to permit larvae to complete their development. This adds to the mortality caused by flushing and predation.

Where marshes are used for sport and recreation, there may be a benefit associated with OMWM (Meredith et al. 1985) and runnelling, although the long term effects need careful monitoring. The specific effects of runnelling on water table depth, substrate characteristics and vegetation density have been insignificant.

Runnelling so far appears also to have had no significant general effect on the local marsh processes of change (Dale and Hulsman 1988). Since the sequence from ditching to OMWM to runnelling is undoubtedly one of diminishing amount/type of habitat alteration, it is reasonable to expect a reduction in amount/type of impact. The general lack of long term and comparative impact studies however, prevents us from making more than a cautious statement about relative effects.

In the USA various authors have estimated that OMWM is cost-effective, over a period of 2–10 years, when compared to insecticide treatment (Telford and Rucker 1973, Shisler 1979). In northern New South Wales, Australia, Easton (1986) estimated that hand dug, shallow recirculation channels would recover their costs in 5–7 years, mainly through savings from reduced insecticide use. Maintenance of these runnels has involved trimming vegetation overhanging the runnels' edges once per year during the last 3 of the 5 years the runnels have been operating at Tweed Heads. In contrast, there has been no clearing of runnels during the 3 years that they have been operating at Coomera Island. Thus, our experience has been that runnels are low maintenance modifications. For several small scale runnelling projects in south east Queensland, Australia, we estimate that construction and maintenance costs for the most expensive would be similar to the costs of chemical treatment over 14–15 years, whereas the cheapest ones would cost less than chemical spraying in the first 5 years. If we take into account the nonmonetary costs of impact on environment, then the gentler arts of OMWM and of runnelling become even more cost effective.

The methods referred to above may be placed on a continuum ranging from pest-focused control to environment-focused management. The pest-focused approach aims to destroy the pest environment, thereby exterminating the pest. In contrast, the approach in environment-focused management is to ask, what is the least we must do to reduce the pest population to an acceptable level? Ditching is an example of a pest-focused approach, whereas OMWM is more environment-focused (than ditching) because it seeks to maintain marsh processes in a more or less natural or at least natural-looking environment. Runnelling is even more environment-focused than OMWM, because minimal modifications are made to the environment to retain it as close as possible to its natural state so as not to hinder its ecological functions.

We have implemented runnelling on a marsh where the water table is usually below the level of the runnels. According to our results the water table is slightly lower near runnels than near pools but not significantly so. Furthermore there was no significant difference between substrate moisture near runnels and pools (Fig. 3b). Thus, in our study area runnelling has not dewatered the marsh.

The suitability of runnelling as a means of mosquito control has still to be tested where the water table is above the bottom of the runnels. We venture that runnelling would function effectively in such an area because (1) water would be retained in runnels at all times allowing larvivorous fish access to mosquito larvae—the runnels would be equivalent to the reservoirs used in OMWM; and (2) the water flow could flush larvae off the marsh. However the effectiveness of runnels in reducing mosquito numbers in such conditions has yet to be tested.

In conclusion, we are of the opinion that the environment-focused approach which we are developing is cost-effective and has the potential to control mosquitoes and minimize effects on the nontarget aspects of the environment. Mechanization may effect further cost savings. It remains to monitor the system over the long term and to explore the applicability of the method of a wider range of habitat types.

ACKNOWLEDGMENTS

We thank the southeast Queensland Contiguous Local Authorities for their support and, in particular, Health Department personnel from the Gold Coast City and Albert Shire Councils. For their contribution, we thank P. Mottram and I. Fanning. For field assistance we thank T. Adams, P. Barnes, G. Blake, D. Bluhdorn, A. Hill, C. Keupers, A. Kuypers and the many Griffith University students who occasionally came to our aid. We also thank the Griffith University Research Grants Committee for financial support.

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